

Cosmic Gamma-ray Bursts
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Abstract

The properties of the cosmic Gamma-ray Bursts (GRBs) are briefly summarized. A detailed bibliography is given with titles of the papers. Two fundamental theoretical problems are pointed out: the problem of the energy source, and the problem of compactness. I demonstrate some inconsistencies in the estimates of the fireball optical thickness that are widely used in the discussion of the latter problem. The possible connection of GRBs with the Dark Matter candidates is mentioned. I argue that GRBs can be produced by collapses or mergers of stars made of one probable Dark Matter candidate, namely the mirror particles. I speculate on the impact that the parameters of the neutrino oscillations might have on the observed properties of GRBs if the latter are the products of mirror star deaths.

Keywords: Gamma-rays: bursts — dark matter — stars: mirror — neutrino oscillations

1 GRB overview

Cosmic Gamma-ray Bursts (GRBs) are irregular pulses of photons peaking near $\sim 0.1 - 1$ MeV, with duration from a fraction of second to minutes. Typical values of their fluence (exposition) are near $F \sim 10^{-7}$ ergs/cm² ~ 1 photon/cm² and are determined primarily by the threshold of the sensitivity of the detectors. Some of GRBs have much higher fluences and fluxes. Here I use astronomical terminology, so the flux is the power of radiation coming through a unit surface. GRBs are discovered three decades ago by the Vela satellites that had a mission to check the observance of the Moscow-1963 nuclear test-ban treaty. Announced by Klebesadel *et al.* (1973), this discovery was quickly confirmed for the burst on 17 January 1972, i.e. GRB 720117 in modern notation, by Soviet Kosmos-461 measurements (Mazets *et al.*, 1974). In subsequent years many satellites and interplanetary missions have observed the bursts. Before the first publication by the Vela group, some dramatic pages in the story were written by the Kosmos-428 team, led by Melioransky: Bratoliubova-Tsulukidze *et al.* (1973) reported about hard X-ray transients, which they later (Babushkina *et al.*, 1975a) found similar to GRBs described by Klebesadel *et al.* (1973). It is remarkable that the short communication of Kosmos-428 results was published even earlier than the Vela paper was submitted! Unfortunately, the data of the Kosmos-428 team (Babushkina *et al.*, 1975b) are believed to be heavily contaminated by the background noise. (For a modern approach to extracting GRB events from the background see Stern *et al.*, 1999).

Here I present only a brief sketch of the GRB properties. For general recent reviews on GRBs see e.g. Piran (1999a,1999b), Tavani (1998), Postnov (1999) and Mészáros(1999).

The time profiles of pulses of gamma ray radiation show a great variety. Figure 1 displays the famous GRB 990123 in four BATSE channels with two prominent spikes. For other bursts Fig. 2 shows a single pulse, and Fig. 3 presents an example of multiple pulses. It is hard to observe any regularity in the time profiles of bursts. See, however, the paper by Stern and Svensson (1996), who claim that they find scale-invariant properties in light curves of GRBs.

The spectra are also rather different from burst to burst. Observations of the GRB spectra (Band *et al.*, 1993) show that, in general, they are well described by a low-energy power law with the exponent α , being exponentially cut off at $E \sim E_0$, and by a high-energy power law with the exponent β . Though the values of (α, β, E_0) can be different for individual bursts, they usually are in the ranges $\alpha \sim [-1.5 \dots 0.5]$, $\beta \sim [-3 \dots -2]$, $E_0 \sim [100 \dots 200 \text{ keV}]$.

Note that in the literature on GRBs there are three forms used for describing the spectra.

1) The photon number spectrum $N(E)$, or $N(\nu)$, with $E = h\nu$, units of photons per second per cm² per unit energy.

2) The differential energy flux density $S(E) = EN(E)$, written also as $S_\nu = h\nu N(\nu)$. In terms of the theory of probability distribution functions (PDFs), this is the first moment of the PDF $N(E)$, see, e.g., the review (Blinnikov, Moessner, 1998). The notation F_ν is often used for the flux instead of S_ν , but I will preferably use the letter F (without subscripts) for the fluence.

3) The second moment of the PDF $N(E)$ is the so called νF_ν distribution, $\nu F_\nu \equiv \nu S_\nu \propto E^2 N(E)$, which peaks where the maximum radiation power comes (per decade of the photon energy).

By default, all the exponents α and β below refer to $N(E)$. The spectra are apparently far from a black body (see Figs. 4, 5), so it is widely believed that the source of gamma radiation is optically thin, i.e. the photon mean free path is larger than the emitting plasma cloud. Yet the spectra are not always described by nonthermal emission in a simple synchrotron shock model (see e.g. Crider *et al.*, 1997) .

It is most probable that the source of gamma radiation, moves to us with extreme relativistic speed, corresponding to the Lorentz factor $\Gamma \gg 1$ (see the section on the compactness problem below). This means that, for example, $\delta t = 10$ ms, the time of signal integration by an observer, corresponds to $\sim 2\Gamma^2\delta t \simeq 5$ hours of emission time if $\Gamma \simeq 10^3$. During this long time the emitting object can expand and cool significantly, so the spectra it produces in the beginning and at the end of the observation interval δt can differ drastically. Therefore, the observed spectrum is formed by an integration of some cooling sample of instantaneous spectra. In principle, the instantaneous spectra can be even black-body (Rozental, Belousova, 1997; Blinnikov *et al.*, 1999), in any case they are not necessarily produced by the synchrotron mechanism (Ryde & Svensson, 1999).

For decades, the nature of GRBs remains mysterious. Even their locations were absolutely uncertain: the distance d could vary in different models from tens of astronomical units ($1 \text{ AU} \approx 1.5 \times 10^{13} \text{ cm}$), up to Gigaparsecs ($1 \text{ Gpc} \approx 3 \times 10^{27} \text{ cm}$). So, for the same fluence $F \sim 10^{-7} \text{ ergs/cm}^2$ the energy $E_{\text{GRB}} = 4\pi F d^2$ could be as low as $\sim 10^{23} \text{ ergs}$ for the nearest locations, and go up to $\sim 10^{49} \text{ ergs}$ for 1 Gpc, if the radiation is not beamed to us but distributed uniformly over 4π . And if F is 4 orders of magnitudes higher (as e.g. for GRB 990123), and/or the distance is larger than 1 Gpc, then the energy release in gamma photons becomes correspondingly higher.

An indirect evidence for cosmological location of GRBs, i.e., on the Gpc distance scale for them, is their isotropic distribution on sky (Prilutskii, Usov, 1975). Before BATSE (Burst And Transient Source Experiment) telescope was launched aboard the Compton Gamma Ray Observatory in 1991, the statistics was poor. Now there are tens of hundreds GRBs in BATSE catalogs, e.g. 1637 in the Fourth BATSE burst catalog (Paciesas *et al.*, 1999), see also a review by Fishman & Meegan (1995) on earlier BATSE results. In spite of a rich statistics, the bursts do not correlate significantly with any known class of objects (although various claims on correlations appear in literature from time to time).

Another hint for cosmological distances of GRBs came from their distribution over fluences F or peak fluxes S . If the sources are distributed uniformly, then their number N_s grows with distance d as $N_s \propto d^3$, and if they have the same intrinsic power then the flux falls as squared distance, $S \propto 1/d^2$. This implies $N_s(S) \propto S^{-3/2}$ if $N_s(S)$ denotes the number of sources with fluxes larger than S . In logarithmic scale one should expect $\log N_s = -(3/2) \log S + \text{const.}$ In reality the distribution is different, see Fig. 6. The deviation of the $\log N_s - \log S$ histogram from a simple $-3/2$ law tells us (Prilutskii, Usov, 1975; Usov, Chibisov, 1975) that either the GRB distribution is centered on us, or that the relations $N_s = N_s(d)$ and $S = S(d)$ are different from the simple expressions that we have used. If we discard the former option, i.e. assume the uniformity of sources, then we are left with the possibility that $N_s = N_s(d)$ dependence is dictated by the volume evolution in expanding Universe. It is often said, that $N_s \propto d^3$ is derived in Euclidean geometry, and the Universe is non-Euclidean. This is not quite correct. The spatial (i.e. 3D) geometry of the Universe can be exactly Euclidean, as is the case for the total energy density $\Omega = 1$ in units of the critical density (for definitions see, e.g. Carroll *et al.*, 1992). The space-time (4D geometry) is always non-Euclidean. What matters, is that the space-time is non-steady, so the comoving volume is time-dependent, and for sources uniformly distributed in the comoving volume, we have another law $N_s = N_s(d)$ because more distant objects live in the younger Universe.

The breakthrough in proving that at least some of GRBs are at cosmological distances occurred in 1997 due to the Italian-Dutch satellite Beppo-SAX. The location of GRBs on sky is known normally with accuracy of tens of degrees, if they are observed by only one gamma-ray

detector. In the past, accurate positions were obtained from a triangulation based on the time delays between several detectors. This requires the processing of data which takes days and weeks. Beppo-SAX has both a gamma-ray detector and a wide field ($\sim 30^\circ$) soft X-ray camera. It could for the first time find an X-ray transient in the same field where a GRB flashed after a delay of only 4-6 hours for processing and could provide X-ray positions with accuracy of a few arcminutes. The technique led to the discovery by Beppo-SAX (Costa *et al.*, 1997) of the first X-ray transient associated with GRB 970228. This allowed follow-ups in X-rays, in visual light (van Paradijs *et al.*, 1997), as well as at radio waves (Frail *et al.*, 1997). The transient counterparts to GRBs are called X-ray, optical (i.e. visual light) and radio ‘afterglows’. For some of them the observations last many months (Zharikov *et al.*, 1998). The number of discovered GRB afterglows is growing continuously. By January 1999 there were 14 X-ray afterglows known (Postnov, 1999). Full information on recent GRBs and their afterglows one can find in Internet at <http://gcen.gsfc.nasa.gov/>.

2 The energy problem

The spectacular discovery of GRB afterglows allowed to measure the redshift, and hence the distance to some of them. The redshift z is defined as $z = (\lambda_{\text{obs}} - \lambda_{\text{lab}})/\lambda_{\text{lab}}$, where λ_{obs} is the observed wavelength of a feature (a line or a jump) in the spectrum of a source, and λ_{lab} is the laboratory wavelength value for the same feature if it can be unambiguously identified. See e.g. Weinberg (1972) and Carroll *et al.* (1992) for the relations connecting z with the distance in standard cosmological models. First, absorption lines with $z = 0.835$ were measured in the spectrum of the counterpart to GRB 970508 (Metzger *et al.*, 1997). Since the absorption was seen in the light of the afterglow, the source could be only more distant. Thus $z = 0.835$ is a lower limit to the redshift of the transient and the GRB that induced it. Later, in some cases the identification of candidate host galaxies was suggested. The outstanding example is the galaxy associated with GRB 971214, its redshift is probably $z = 3.418$ (Kulkarni *et al.*, 1998). Yet, there can be doubts in correctness of this value, since there is only one emission line discernible above the noise level of the spectrum of this very distant galaxy, and the identification relies heavily on the assumption that the line is Lyman- α . Much more convincing is the observation of a system of absorption lines with $z = 1.600$ in the spectrum of the afterglow of GRB 990123 (Kulkarni *et al.*, 1999). The energy output up to 3.4×10^{54} ergs $\approx 1.9 M_\odot c^2$, with M_\odot being the solar mass, is implied by the redshift $z = 1.600$. The huge energy release in some of the bursts poses extremely hard questions to theorists who try to explain these superpowerful events. Even if a beaming is invoked, which reduces the energy budget by a couple of orders of magnitude, this is still too high for conventional models that involve collapses or mergers of objects with masses on M_\odot scale. (Blinnikov *et al.*, 1984; Eichler *et al.*, 1989; Paczyński, 1986; Janka and Ruffert, 1996, Ruffert *et al.*, 1997).

This is the *energy problem* of GRB central engine. For objects with huge masses (Prilutskii, Usov, 1975), which have high energy resources, it is harder to explain the short time-scale variability (see below the section on the compactness problem) as well as the statistics of events.

3 The compactness problem

The time-scale of the variability of the gamma-ray flux during a burst can be $\delta t \sim 10^{-2}$ seconds, and even shorter. The naive estimate for the source at rest implies that the size of the emitting

region must be $R \lesssim c\delta t$, as small as $R \sim 3 \times 10^3$ km. With c being the speed of light, I put $c = 1$ hereinafter in formulae for simple relativistic transformations or in the expressions for elementary processes, so this estimate gives $R \sim \delta t$ light seconds. I write down c explicitly in formulae written in technical units and when microscopic and macroscopic quantities appear simultaneously. The enormous number of gamma photons in such a small volume should produce electron-positron pairs via the process $\gamma + \gamma \rightarrow e^+ + e^-$ if the energy of the photon collision at angle θ is above the threshold, i.e. $s > 4m_e^2$ where s is the total squared c.m.s. energy,

$$s = 2E\epsilon(1 - \cos \theta), \quad (1)$$

if the photon energies are E and ϵ . The emitting region can become optically thick, i.e. the mean free path l_γ of a photon before a creation of an e^+e^- pair can become less than R , so the optical depth $\tau_{\gamma\gamma} \equiv R/l_\gamma > 1$. Then the photon energy will degrade and the spectrum will be thermalized. This conflicts with the observed nonthermal spectra, they have rather large energy in the power-law tails above the threshold, thus leading to the so called *compactness problem* of GRBs (Guilbert, Fabian & Rees, 1983).

Some bright GRBs detected at standard range of a few hundred keV have also been seen at much higher energies (above 10 MeV). An outstanding example is GRB 940217, which had the most energetic GRB photon detection to date, up to ~ 18 GeV. “Such observations imply that these bursts are optically thin to photon-photon pair production at all observed energies, for target photons both internal and external to the source” (Baring, Harding, 1997).

The absorption of gamma-quanta by a photon gas was considered by Nikishov (1961), Gould, Schröder (1967), Brown *et al.* (1973). These papers have dealt with an isotropic photon gas. Here I present only crude estimates, because the situation in GRBs can be far from isotropy, even inside the source of radiation.

We will consider only the process of single-pair creation $\gamma + \gamma \rightarrow e^+ + e^-$, because the processes of multiple-pair creation are not important for the energies typical for GRBs (Brown *et al.*, 1973). The cross-section $\sigma_{\gamma\gamma}$ of the process of single-pair creation can be easily expressed through s (e.g. Akhiezer, Berestetskii, 1965). For our estimates we simply note that $\sigma_{\gamma\gamma}$ grows quickly above the threshold. The maximum of $\sigma_{\gamma\gamma}$ is reached at $s^{1/2} = 1.40 \times 2m_e$ (Svensson, 1982). At reasonable, mildly relativistic, energies above the threshold the cross-section is of the order of r_e^2 , where $r_e = e^2/m_e$ is the classical electron radius. For high energies the cross-section falls:

$$\sigma_{\gamma\gamma} = 4\pi r_e^2 \frac{m_e^2}{s} [2 \ln(s^{1/2}/m_e) - 1], \quad s \gg m_e^2. \quad (2)$$

If the photon number density is $n_{\gamma 1}$, then the rate of pair production in a photon beam colliding with another beam with density $n_{\gamma 2}$ at an angle θ is

$$n_{\gamma 1} n_{\gamma 2} \sigma_{\gamma\gamma}(s)(1 - \cos \theta) \quad (3)$$

(Nikishov, 1961; Gould, 1971; Weaver, 1976). One can estimate the absorption probability per unit path length, i.e. the inverse mean free path l_γ^{-1} of a photon with energy E , using (2) and ignoring logarithms, as well as all angle dependencies:

$$\frac{1}{l_\gamma} \sim \int_{2m_e^2/E}^{\infty} d\epsilon n(\epsilon) \sigma_{\gamma\gamma}(2E\epsilon), \quad (4)$$

where $n(\epsilon)$ is the number of photons per unit volume per unit energy interval and I have put $\cos \theta = 0$ in (1) and (3). For the case of the *isotropic* distribution of photons an accurate

expression for the power law spectrum is obtained by Gould, Schröder (1967). If we assume that the spectral distribution of photons in the source is a power law, $n(\epsilon) = C\epsilon^\beta$, then we get from (4)

$$l_\gamma^{-1} \sim Cr_e^2(m_e^2/E)^{\beta+1}. \quad (5)$$

(Normally, in GRBs $\beta \sim [-2 \div -3]$, so the absorption probability grows as $E^{[1 \div 2]}$.)

We estimate the photon number density $n(\epsilon)$ in the following way (cf. Carrigan, Katz, 1992). Take the observed number flux $N(\epsilon)$ (say, in units of photons per second per cm^2 per erg), and find the flux at the source surface at distance d from the solar system, it will be $N(\epsilon)(d/R)^2$, if the surface is of the radius R . Divided by speed of light c , this flux gives the photon number density $n(\epsilon)$. If the observed number flux is

$$N(\epsilon) = N(\epsilon_0)(\epsilon/\epsilon_0)^\beta,$$

where ϵ_0 is just a typical energy of observed gamma photons, say, $0.5 \text{ MeV} \approx m_e$, then we get the constant C in the expression (5):

$$C = \frac{d^2}{cR^2} \frac{N(\epsilon_0)}{\epsilon_0^\beta}.$$

Now the optical depth of the photon creation of pairs, $\tau_{\gamma\gamma} \equiv R/l_\gamma$, is

$$\tau_{\gamma\gamma} \sim \frac{d^2}{cR} \frac{N(\epsilon_0)}{\epsilon_0^\beta} r_e^2 \left(\frac{m_e^2}{E} \right)^{\beta+1}. \quad (6)$$

For $E = \epsilon_0 = m_e$ this gives:

$$\tau_{\gamma\gamma} \sim \frac{d^2}{cR} N(\epsilon_0) r_e^2 m_e = \frac{d^2}{cR} S(\epsilon_0) r_e^2. \quad (7)$$

I have preserved the symbol c for speed of light in the last expressions for the case when the fluxes N and S are measured in technical units. It is easy to see that we have got really dimensionless quantity $\tau_{\gamma\gamma} = R/l_\gamma$, since the dimension of the spectral flux density S is $\text{cm}^{-2} \text{s}^{-1}$.

We take for the typical energy scale of GRB photons the electron mass m_e , and assume that the burst has \mathcal{N} pulses with duration δt each and with the typical flux S . The number of pulses \mathcal{N} can be as high as hundreds, and their duration like 10 ms or even shorter. Let $f_{0.5}$ be the fraction of the total energy E_{GRB} that comes in the decade of photon spectrum near $\epsilon_0 = 0.5 \text{ MeV} \sim m_e$. Then $f_{0.5} E_{\text{GRB}} \sim m_e S d^2 \mathcal{N} \delta t$, and

$$\tau_{\gamma\gamma} \sim f_{0.5} \frac{E_{\text{GRB}} r_e^2}{m_e \delta t^2 \mathcal{N}} \approx 10^{12} \frac{f_{0.5}}{\mathcal{N}} \frac{E_{\text{GRB}}}{10^{49} \text{ ergs}} \left(\frac{\delta t}{10 \text{ ms}} \right)^{-2}, \quad (8)$$

or, expressed through the fluence $f_{0.5} F \sim m_e S \mathcal{N} \delta t$,

$$\tau_{\gamma\gamma} \sim 10^{12} \frac{f_{0.5}}{\mathcal{N}} \frac{F}{10^{-7} \text{ ergs/cm}^2} \left(\frac{d}{1 \text{ Gpc}} \right)^2 \left(\frac{\delta t}{10 \text{ ms}} \right)^{-2}. \quad (9)$$

One can find another way for estimating the optical depth $\tau_{\gamma\gamma}$ in the astrophysical literature, see, e.g. Piran (1996,1999a,1999b). One denotes by f_p the fraction of photons in a burst that satisfy the threshold condition for pair creation. Take the fluence F , find the energy of the

burst $E_{\text{GRB}} = 4\pi F d^2$, multiply by f_p/m_e , divide by volume $4\pi R^3/3$ and get the photon number density:

$$n_\gamma \sim \frac{f_p F d^2}{R^3 m_e}.$$

Then the optical depth would be

$$\tau_{\gamma\gamma} \sim \frac{f_p r_e^2 F d^2}{R^2 m_e},$$

or, for $R \sim \delta t$,

$$\tau_{\gamma\gamma} \sim 10^{12} f_p \frac{F}{10^{-7} \text{ ergs/cm}^2} \left(\frac{d}{1 \text{ Gpc}} \right)^2 \left(\frac{\delta t}{10 \text{ ms}} \right)^{-2}. \quad (10)$$

This expression is wrong: it overestimates the photon density by a factor \mathcal{N} . It is unwise to take the fluence F in the estimate of n_γ for bursts with multiple short pulses. Suppose, that a burst has ~ 1000 pulses, it is clear, that the concentration of photons n_γ in the source will be 1000 times lower than in another GRB with the same fluence and at the same distance d that has only one short pulse. Yet nothing changes in the estimate (10). The correct, though crude, estimate is given by expressions (8) and (9).

The compactness problem arises because of the conflict of the naive estimate of the source size R with the observed nonthermal GRB spectra. The conflict can be resolved if one supposes that the emitting region moves towards the observer with an extreme relativistic speed with Lorentz factor $\Gamma \gg 1$. Then, as is shown in the next paragraph, the actual size would be $\sim \Gamma^2 \delta t$, and the optical depth becomes correspondingly smaller (Guilbert, Fabian & Rees, 1983, Paczyński, 1986, Goodman, 1986, Krolik & Pier, 1991, Rees & Mészáros, 1992).

Let us suppose that the emitter is moving towards the ‘terrestrial’ observer with the velocity v corresponding to $\Gamma = (1 - v^2)^{-1/2}$. Here we assume that all clocks are synchronized in the observer’s rest frame, i.e. the effect under consideration is purely kinematic, moreover it is Galilean, not truly relativistic (in the sense that Relativity plays no role in its explanation). The Lorentz factor Γ is here simply a measure of the deviation of v from speed of light, and nothing else. The Fig.7 shows that the source emits gamma rays while moving with the speed v during time $t_0 \dots t_1$. At the end of the process the photons emitted at the moment t_0 are ahead of the source for the distance of only $(1 - v)(t_1 - t_0)$. Thus, the difference in the arrival times for first and last photons is $\delta t = (1 - v)(t_1 - t_0) = (t_1 - t_0)/2\Gamma^2$, and the observed duration of the burst is shorter than the emission time by a factor of $1/2\Gamma^2$, since for $v \approx 1$ one finds $1 - v \approx 2\Gamma^2$. Instead of our original estimate for the emitting region $R \sim \delta t$ we may now have $R \sim 2\delta t\Gamma^2$. The expression (7) shows that the optical depth goes down as Γ^{-2} due to this effect.

There are other, truly relativistic, effects. Let the photons be observed at the energy E_{obs} . If the emitter moved towards an observer with a relative velocity v then the photon energy at the source was $E_{\text{obs}}/(1 + v)\Gamma$, due to relativistic Doppler factor $(1 + v)\Gamma \approx 2\Gamma$ for $\Gamma \gg 1$. So only the photons with $E_{\text{obs}} > 2m_e\Gamma$ are above the threshold of the pair production while they are in the source itself (although the softer photons can be attenuated by other photons outside the source). If $N(E) \propto E^\beta$ (and $\beta \sim [-2 \div -3]$), this reduces the number of photons, able to produce pairs, and the optical depth at the source by a factor Γ^β at least.

By definition, the flux $S(E) \equiv S_\nu = \int d\Omega I_\nu(\Omega) \cos \theta$, where I_ν is the brightness and θ is the angle between the direction of a beam of photons and the normal to the detector surface. The brightness is defined as the power coming per unit area per unit frequency per unit solid angle. If $f_\nu(\Omega)$ is the photon occupation number for the frequency ν in the direction Ω , then $I_\nu = (2h\nu^3/c^2)f_\nu$. The Lorentz invariance of the photon distribution in the phase space f_ν

implies that the brightness I_ν transforms as ν^3 . Let us assume that an observer is moving with the same speed v with large Γ and in the same direction as a distant source and measures its flux at the same world point as a ‘terrestrial’ detector. It is easy to show that the flux $S_\nu \equiv S_{\text{com}}(E)$, measured in the frame comoving with the source, is lower than the one measured for the terrestrial detector by the Doppler factor: $S_{\text{com}}(E_{\text{com}}) = S(E_{\text{obs}})/[(1+v)\Gamma]$. For the total flux and for the νS_ν distribution the factor is $1/[(1+v)\Gamma]^2$. Moreover, due to the Lorentz transformation of coordinates, $x_{\text{com}} = \Gamma(x + vt)$, the distance in the comoving frame is $d_{\text{com}} = d/(1+v)\Gamma$, if $x = d$ is the distance ascribed by the terrestrial observer to the source position for the moment when radiation was emitted (if the photons are detected at $t = 0$ they were emitted in our frame at $t = -d$). Thus, the luminosity (i.e. the power of the source emission) per unit energy can be overestimated by the terrestrial observer by a factor of Γ^3 , and the total luminosity by a factor of Γ^4 (Lightman *et al.*, 1975, problem 5.11). One should be careful in measuring distances in relativistic situations: if we are interested in the distance D to the source at the moment $t = 0$ we see that $d_{\text{com}} = \Gamma D$, so $D \ll d_{\text{com}} \ll d$.

The combination of all effects leads to the division of the optical depth by a factor of Γ to a high power, like $\sim 5 - \beta$ or more. The power depends on the geometry, beaming etc. I have presented the estimate for the case when the photons are being created and interacting in the source itself. Another approach to relativistic motion in GRBs is pursued in a number of papers. For the test photons with energy E , which have left the source already, the factor of Γ^4 for transformation of the luminosity does not enter. Still a factor of $\Gamma^{\beta-2}$ at least does suppress the optical depth (from the spectrum, and from larger R). The aberration effects are more important for the photons external to the source. Fenimore *et al.* (1993), Woods, Loeb (1995) consider the latter situation: they check at which value of Γ the highest energy photons (say, GeV external photons) are able to escape the pair production with the lower energy photons *outside* an opaque, relativistically expanding source. A very detailed analysis for all geometries is given by Baring & Harding (1997). Summarizing the results of those studies, we conclude that $\Gamma \sim 10^2 \div 10^3$ can help in reducing the optical depth below unity.

Another option for solving the compactness problem stems from a chance to have $\cos\theta$ in (1) and (3) exactly equal to zero. Imagine that we are sitting in a beam of a gamma-ray laser pointed to us. The coherent photons are not able to collide, and there is no pair creation. The picture seems quite fantastic, since we observe rather smooth energy distributions and do not see prominent lines in GRB spectra. To reduce the statistics of GRB events we need the solid angle of the radiation to be rather large. It is hard to imagine gamma-ray laser guns pointing to different directions, while their beams do not collide, but who knows! I failed to find a model like this in the literature (see, e.g. the list of more than 100 GRB models compiled by Nemiroff, 1994), but the idea of extremely narrow beams with solid angles $\sim 10^{-6}$ is being pushed by Dar (1998), Dar, Plaga (1999) in a different context (not invoking a laser mechanism).

4 GRB models and their baryonic contamination

If the huge energy required for explanation of distant GRBs is quickly injected into the interstellar matter then it will inevitably lead to a formation of a hot cloud of rapidly expanding plasma. This picture is similar to the fireball formation resulting in nuclear explosions in the Earth’s atmosphere (Sedov, 1959; Zel’dovich, Raizer, 1966). The fireball model of GRB emission (Rees & Mészáros, 1992) is semi-qualitative, and has some *ad hoc* assumptions (like formation of the so called ‘internal’ shocks of mysterious nature: Rees & Mészáros, 1994), yet it has led

to partially successful explanations of some observed features of GRBs, and especially of their afterglows. See numerous references in Piran (1999b) and Mészáros(1999). Those authors claim that the fireball theory is an absolute success (though it does not explain the physical nature of the ‘central engine’ of a GRB). Other opinions are also expressed in literature. E.g. Dar (1998) writes: “The observed afterglows of gamma-ray bursts (GRBs), in particular the afterglow of GRB 970228 after 6 months, seem to rule out, as the origin of GRBs, relativistic fireballs driven by the mergers or accretion-induced collapse of compact stellar objects in galaxies. GRBs can be produced by superluminal jets from such events.” Other options for producing the radiation are also possible, e.g. heavy blobs (or ‘bullets’) running into the circumstellar matter (Blinnikov *et al.*, 1999; Heinz, Begelman, 1999).

In any case, if a fireball forms, it must not be heavily contaminated with baryons. If the Lorentz factor Γ is $\sim 10^3$ then the presence of a small baryon mass $M_b \sim 10^{-3}M_\odot$ will require enormous energy release of the order of the solar mass, $M_b\Gamma \sim M_\odot$, even if the total photon energy E_{GRB} is several orders of magnitude lower. Another problem with baryons is their high opacity due to photoeffect in keV range which is shifted to MeV range with $\Gamma \sim 10^3$. Some amount of baryons, like $\sim 10^{-7} \div 10^{-5}M_\odot$ is OK, and it is even needed in the fireball models to preserve the energy produced by the ‘central engine’ in the form of kinetic energy which is transported to the optically thin regions and transformed into photon energy in shock waves and their collisions.

The low optical depth and the ultrarelativistic motion require that the fireball should be very clean. Yet the majority of GRB models suggested so far are producing rather ‘dirty’ fireballs. Those models are trying to produce an event on the supernova energy scale normally do involve an acceleration of the baryonic matter on the same scale as at stellar explosions, i.e. an appreciable fraction of M_\odot . So, to avoid additional complications with the energy problem one should find a mechanism of producing a GRB with low baryon loading.

The mechanism that can act outside the body of a collapsing star is a chain of reactions:

$$\nu + \bar{\nu} \rightarrow e^- + e^+ \rightarrow \gamma's$$

The process of neutrino annihilation was put forward in relation with GRB models by Berezhinskii & Prilutskii (1985, 1987), and discussed in supernova models by Cooperstein *et al.* (1986, 1987), Goodman *et al.* (1987). The pairs $\nu\bar{\nu}$ of all flavors are copiously produced during collapse. Many neutrino processes producing positrons, and their annihilation with electrons, $e^- + e^+ \rightarrow \gamma's$ were proposed for GRB models already by Bisnovatyi *et al.* (1975). Berezhinskii & Prilutskii (1985, 1987) used the predictions for the neutrino spectra computed for stellar collapse by Nadyozhin (1978), Nadyozhin, Otreshchenko (1980). A lot of work has been done during last two decades in improving physics in the stellar core collapse computations, see e.g. Messer *et al.* (1998) and references therein, but the main features of the neutrino spectra are robust and change only slightly in comparison with Nadyozhin’s work.

In view of the importance of the process of pair creation by neutrinos I present some estimates for it. The cross-section $\sigma_{\nu\bar{\nu}}$ is

$$\sigma_{\nu\bar{\nu}} \simeq \frac{8\xi^2 \pm 4\xi + 1}{6\pi} G_F^2 s$$

in ultrarelativistic limit, $s \gg m_e^2$. Here s is again the total squared energy in the center-of-mass frame, but E and ϵ in (1) are now the neutrino energies. The ‘+’ sign is for $\nu_e\bar{\nu}_e$ and the ‘−’ sign is for $\nu_\mu\bar{\nu}_\mu$ and $\nu_\tau\bar{\nu}_\tau$, and $\xi = \sin^2 \theta_W$. (Berezhinskii & Prilutskii, 1985, 1987, write down $\sigma_{\nu\bar{\nu}}$ for the general case, but, with the typical neutrino energies $\sim 10 \div 20$ Mev, the relativistic limit is

OK). For electron neutrinos the cross-section is almost an order of magnitude larger, since the charge current contributes to the process appreciably. But this is also the reason why the average energy of ν_e is a factor 2 to 3 lower than for ν_μ and ν_τ : the medium is more transparent for non-electronic species and we see deeper, hotter layers of a collapsing star in ν_μ 's and ν_τ 's. For example, in their computations of the collapse in merging neutron star scenario, Ruffert *et al.* (1997) find that “after the two neutron stars have merged, luminosities up to several 10^{52} erg/s are reached for every neutrino species and the average energies of ν_e leaking out of the merger are 10–13 MeV, of $\bar{\nu}_e$ they are 19–21 MeV, and of heavy-lepton neutrinos around 26–28 MeV”. So, the net effect for electron pair production is comparable for all neutrino species.

Let us give a dimensional estimate of the neutrino optical depth, $\tau_{\nu\bar{\nu}}$, for annihilation of ν_i and $\bar{\nu}_i$ into e^+e^- -pairs neglecting blocking effects in the phase spaces of e^- and e^+ and ν 's, since we are interested in the process outside the collapsing body where occupation numbers are not close to 1. The procedure is very similar to the estimates of the photon optical depth $\tau_{\gamma\gamma}$, but now we have to be more careful with angular dependencies. If the neutrino number density is n_ν , then the rate of the annihilations in a beam colliding with a beam of $\bar{\nu}$ at an angle θ is

$$n_\nu n_{\bar{\nu}} \sigma_{\nu\bar{\nu}}(s)(1 - \cos \theta),$$

the same angular factor as for photons in (3). Then the probability of the process in the beam traversing the distance dr is by definition

$$d\tau_{\nu\bar{\nu}} = n_\nu \sigma_{\nu\bar{\nu}}(1 - \cos \theta) dr.$$

We estimate n_ν from the neutrino luminosity L_ν (the power of the neutrino emission) at a radius R when E is an average energy of neutrinos:

$$L_\nu \sim n_\nu E c R_\nu^2.$$

This gives

$$d\tau_{\nu\bar{\nu}} \sim \frac{L_\nu}{E c R_\nu^2} G_F^2 s (1 - \cos \theta) dr. \quad (11)$$

So in the region near the neutrinosphere of radius R_ν (a surface of last scattering of neutrinos in a collapsing object), where $s \sim E^2$ and for $dr \sim R_\nu$ we get, putting $\cos \theta = 0$,

$$\tau_{\nu\bar{\nu}} \sim \frac{L_\nu}{c R_\nu} G_F^2 E. \quad (12)$$

Substituting the values typical for the stellar collapse, like $L_\nu \sim 10^{52}$ erg/s, $E \sim 10$ MeV, $R_\nu \sim 20$ km, and taking $G_F^2 = 5.3 \times 10^{-44} \text{cm}^2/\text{MeV}^2$, we find $\tau_{\nu\bar{\nu}} \simeq 0.1$. One should not take this number very seriously, since we have neglected all numerical factors like π 's in our estimate. Yet it is quite reasonable and can be easily understood if one remembers the definition of the neutrinosphere: the optical depth there is unity for the processes of ν interaction with electrons and nucleons, and the number density of neutrinos is an order of magnitude lower than of the latter, while the cross-section is always $\sim G_F^2$ times the typical energy squared.

The possibility of a GRB to appear during a bare core collapse was suggested by Dar *et al.* (1992) who assumed a GRB to be a result of the neutrino-antineutrino pair creation and annihilation. Although the idea of involving $\nu\bar{\nu}$ annihilation for producing GRBs is very appealing, the model by Dar *et al.* (1992) should be rejected on the grounds of being too contaminated by baryon loading, see e.g. Woosley (1993).

A plausible way of forming GRBs at cosmological distances involves binary neutron star merging (originally proposed by Blinnikov *et al.*, 1984; see more recent references and statistical arguments in favor of this model in Lipunov *et al.*, 1995). However, as detailed hydrodynamical calculations currently demonstrate, this mechanism also fails in producing powerful clean fireballs (Janka and Ruffert, 1996; Ruffert *et al.*, 1997). On the GRB models with a moderately high baryon loading see Woosley (1993), Ruffert & Janka (1998), Kluźniak & Ruderman (1998), Fuller & Shi (1998), Fryer & Woosley (1998), Popham, Woosley & Fryer (1999).

For illustration of a possible construction of the GRB central engine I reproduce a figure from the paper by Janka *et al.* (1998), see Fig. 8. The merging of two neutron stars is inevitable in a neutron star binary system due to gravitational radiation (Clark, Eardley, 1977; Blinnikov *et al.*, 1984). After the merging the stars may form a black hole and a hot torus (an ‘accretion disk’) of a hot dense matter which emits neutrinos of all flavors. The annihilation of $\nu + \bar{\nu} \rightarrow e^- + e^+$ creates pairs and a jet able to produce a short burst of gamma radiation.

A jet of a longer duration (tens of seconds) is investigated in the paper by Macfadyen, Woosley (1999). It is formed by the accretion of the dense matter onto a massive black hole formed inside a very massive star at the latest stages of its life. The jet can be very powerful and can punch a hole through the body of the star. The computations are not yet able to follow all stages of this process which can lead to the explosion of the star. Macfadyen and Woosley (1999) write: “During the tens of seconds that it takes the star to come apart, if energy input continues at their base, the relativistic jets created in the deep interior erupt from the surface of the star and break free. Their relativistic Γ rises. They then travel hundreds of AU’s before making the GRB.”

A GRB with a reasonable energy can be produced, and the authors believe that it will not be overloaded with baryons, but one has to await the detailed computations of the whole process. It may happen that the same energy release from $\nu\bar{\nu}$ that sustains jets, forces too many baryons to go in the same direction.

Knowing $\tau_{\nu\bar{\nu}}$ one can estimate the power, taken from the total luminosity, that is from L_ν , which goes into the creation of e^-e^+ pairs. When $\tau_{\nu\bar{\nu}} < 1$ the power deposited by neutrinos is just $\tau_{\nu\bar{\nu}}L_\nu$. Using our expression (12) it is easy to understand the numerical results by Ruffert *et al.* (1997) who find in our notation

$$\tau_{\nu\bar{\nu}} = (2 \dots 3) \cdot 10^{-3} \frac{L_{\nu e}}{1.5 \cdot 10^{52} \text{erg/s}} \frac{\langle E \rangle}{13 \text{ MeV}} \frac{20 \text{ km}}{R_d} \quad (13)$$

for the disk or torus geometry with a typical radius R_d . This is an order of magnitude smaller than our crude estimate (12) just because the geometrical factors and accurate coefficients were ignored in (12).

For large distances, $r \gg R_\nu$, the optical depth falls sharply, since s contains $1 - \cos \theta$ in (1) which goes down as $(R_\nu/r)^2$, the same power is added by $1 - \cos \theta$ in (11). Finally, n_ν drops also as $(R_\nu/r)^2$ and, after integration over dr in (11) all that leads to a fast decrease, $\propto r^{-5}$, of the rate of pair creation by $\nu\bar{\nu}$ with the growing distance from the collapsing body.

One should note also that the spectrum of the neutrino is close to the blackbody one (i.e. it is a Fermi distribution with zero chemical potential, Nadyozhin, 1978; Nadyozhin, Otreshchenko, 1980). So, usually L_ν and E are not independent in (12). Expressed through the blackbody temperature T , the typical energy is $\langle E \rangle \simeq 3T$ for T in energy units (or $\langle E \rangle \simeq 3kT$ for T in Kelvins) and $n_\nu \simeq (kT/\hbar c)^3$, then

$$L_\nu \sim \left(\frac{kT}{\hbar c} \right)^4 c R_\nu^2,$$

and (12), i.e. the expression for the optical depth above the radial distance r , when the neutrinosphere is located at R_ν , takes the form

$$\tau_{\nu\bar{\nu}} \sim G_F^2 \frac{(kT)^5}{(\hbar c)^3} R_\nu \left(\frac{R_\nu}{r} \right)^5. \quad (14)$$

Cf. Berezhinskii & Prilutskii (1987), who find essentially the same expression in their Eq.(8), but be careful with their numerical factor.

In a recent paper Salmonson, Wilson (1999) consider the General relativistic effects for $\nu + \bar{\nu} \rightarrow e^- + e^+$ and claim that the efficiency of this process is enhanced over the Newtonian values up to a factor of more than 4 (sometimes up to a factor of 30) in various regimes of collapse.

Vietri & Stella (1998) and Spruit (1999) suggest (on the qualitative level) other models that probably have a small baryon contamination. In these models the magnetic field plays a crucial role. A very strong magnetic field of a rapidly rotating neutron star as a source of GRB was proposed by Usov (1992). Without the detailed quantitative computations, it is hard to check that one can derive the huge energy, required by the most recent GRB observations, from the ‘magnetic’ models. A good example here is the magneto-rotational supernova mechanism that was proposed by Bisnovatyi-Kogan (1970) and required further elaborating during three decades to get a definite answer, see Ardeljan *et al.* (1996a,b).

5 Neutrino Oscillations

A very interesting idea, involving neutrino oscillations, was put forward by Kluźniak (1998) in an attempt to solve the problem of the baryon loading in the neutrino driven GRBs. The Super-Kamiokande data (Fukuda *et al.*, 1998; see also Shiozawa, 1999, presented at this School) suggest that vacuum oscillations of the μ neutrino are possible $\nu_\mu \rightleftharpoons \nu_x$, where ν_x may be ν_τ or a non-interacting ‘sterile’ neutrino.

The probability of the neutrino transformation between two flavor eigenstates $\nu_\alpha \rightleftharpoons \nu_\beta$ in vacuum, in terms of the distance d from the source, is

$$P(\nu_\alpha \rightleftharpoons \nu_\beta)(d) = \sin^2 2\theta_v \sin^2 \left(\frac{\delta m^2 c^3 d}{4\hbar E} \right). \quad (15)$$

Here E is the neutrino energy, $\delta m^2 \equiv |m_2^2 - m_1^2|$ for two mass eigenstates 1 and 2, and θ_v is the vacuum mixing angle. The expression (15) is equivalent to

$$P(\nu_\alpha \rightleftharpoons \nu_\beta)(d) = \sin^2 2\theta_v \sin^2 \left(1.27 \frac{\delta m^2 (\text{eV}) d (\text{km})}{E (\text{GeV})} \right), \quad (16)$$

which was used in many lectures presented at this school.

The Super-Kamiokande data are consistent with $\sin^2 2\theta_v \simeq 1.0$ and $\delta m^2 \sim 10^{-3} (\text{eV})^2$. For $E \sim 10 \text{ MeV}$ and $\delta m^2 \sim 10^{-3} (\text{eV})^2$ the oscillation length

$$L_o = \frac{4\pi\hbar c E}{\delta m^2 c^4} \quad (17)$$

comes out to be on the order of tens kilometers, i.e. it is comparable with the size of collapsing stellar objects. This opens interesting possibilities for GRB models.

Kluźniak (1998) suggested that the ordinary muon neutrinos, born by a collapsing body, do oscillate into sterile ones, go out to the regions relatively free of baryons, and then transform back into ordinary neutrinos. They deposit their energy into electron-positron pairs in vacuum and eventually produce the GRB event.

For this scenario the difficulty is similar to the one encountered in the models discussed previously: if the oscillation length is comparable with the size of the collapsing body then the baryonic contamination is unavoidable. So L_o must be much larger than the neutrinosphere R_ν . If it is too long then a very small number of neutrinos will annihilate, see (14). Another difficulty is noted by Volkas and Wong (1999): “there is no reason to assume that only μ -type neutrinos are (thermally) emitted. Thus *all* neutrino flavors must individually oscillate into a sterile neutrino to substantially eliminate $\nu\bar{\nu}$ annihilation in the baryonic region. The conversion of ν_μ to ν_s (and their antiparticles) alone will not solve the baryon-loading problem.”

In this lecture I propose the possibility of drastic extension for the GRB model with neutrino oscillations by invoking stars made of the so-called mirror matter (the first version of this proposal appeared during this Winter School in Blinnikov, 1999). The sterile neutrino should be abundantly produced by the mirror matter during collapses or mergers of stars, made of mirror baryons. If the sterile neutrinos oscillate to ordinary neutrinos, they do this in the space practically free of ordinary baryons, and this can give birth to a powerful gamma-ray burst.

6 The concept of mirror matter

The concept of mirror matter stems from the idea of Lee & Yang (1956) who suggested the existence of new particles with the reversed sign of the parity violating asymmetry in weak interactions. Lee and Yang believed that these particles (whose masses are degenerate with the masses of ordinary particles) could participate in the ordinary strong and electromagnetic interactions. Later, in their seminal paper, Kobzarev, Okun & Pomeranchuk (1966) argued that this conjecture was not correct, and that the ordinary strong, weak and electromagnetic interactions were forbidden for the new particles by experimental evidence. Only gravity and super-weak interaction is allowed for their coupling to the ordinary matter. But if the new particles really mirror the properties of ordinary ones, then there must exist new, “mirror”, photons, gluons etc., coupling the mirror fermions to each other. Thus, the possibility of existence of the mirror world was demonstrated first by Kobzarev *et al.* (1966), and the term “mirror” was coined in that paper. The particle mass pattern and particle interactions in the mirror world are quite analogous to that in our world, but the two worlds interact with each other essentially through gravity only. It is shown in the cited paper that a world of mirror particles can coexist with our, visible, world, and some effects that should be observed are discussed.

Later the idea was developed in a number of papers, e.g. Okun (1980), Blinnikov & Khlopov (1983), and the interest to it is revived recently in attempts to explain all puzzles of neutrino observations by Foot & Volkas (1995), Berezhiani & Mohapatra (1995), Berezhiani *et al.* (1996), Berezhiani (1996), Silagadze (1997).

It was shown by Blinnikov & Khlopov (1983) that ordinary and mirror matter are most likely well mixed on the scale of galaxies, but not in stars, because of different thermal or gasdynamic processes like SN shock waves which induce star formation. It was predicted that star counts by Hubble Space Telescope (HST) must reveal the deficit of local luminous matter if the mirror stars do really exist in numbers comparable to ordinary stars and form a galaxy with properties similar to our spiral Milky Way. Then the mirror stars and mirror gas contribute

significantly to the gravitational potential of galactic disk. Recent HST results (Gould *et al.*, 1997) show the reality of the luminous matter deficit: e.g., instead of 500 stars expected from the Salpeter mass function in the HST fields investigated for the range of absolute visual magnitudes $14.5 < M_V < 18.5$ only 25 are actually detected. It is found that the mass distribution function of weak stars does not follow the power law, known for massive stars, but has a maximum near $M \sim 0.6M_\odot$, and then falls abruptly. So the low mass stars do not contribute much to the total luminous mass, contrary to what was thought previously. The total column density of the galactic disk, $\Sigma \approx 40M_\odot\text{pc}^{-2}$ is a factor of two lower than published estimates of the dynamical mass of the disk, that reflects the gravitating mass (Gould *et al.*, 1997). If true, this result is a direct evidence in favor of existence of local invisible matter.

Unfortunately, astronomers cannot reach an agreement on this subject. Recent Hipparchos results (Holmberg, Flynn, 1999) do not see a local deficit of visible matter. If Hipparchos is more correct than HST, this does not exclude the existence of the mirror stars. This tells that the mirror stars can be distributed around us in the extended halo of our Galaxy, and do not form a very flattened disk system as massive stars in spirals.

It should be remembered that till this moment I have discussed a contribution of invisible stars to the gravity of the galactic disk only, which has more to do with the local Oort limit (see e.g. Oort, 1965) than with the dark matter found in halos of other galaxies. There are virtually no doubts in existence of the halo dark matter (DM) (see a historical review by Van den Berg, 1999). The modern paradigm is that the DM must be ‘cold’ (Navarro *et al.*, 1997), it cannot consist predominantly, e.g., from light massive neutrinos, which give ‘hot’ DM, but the nature of the DM remains unknown. Recent results show that many properties of the cold DM must be similar to ordinary baryonic matter (Burkert, Silk, 1999). This makes the mirror matter (or other types of the ‘ghost’ matter) an attractive candidate for DM (or at least to an essential fraction of DM). Other references on the subject see also in Mohapatra & Teplitz (1999).

The distribution of mirror stars in the halo of our galaxy is supported by observations of gravitational microlensing events. Okun (1980), Blinnikov & Khlopov (1983), Berezhiani (1996) have pointed out that mirror objects can be observed by the effect of gravitational lensing. After the discovery of MACHO (Alcock, 1997) microlensing events, I have discussed their interpretation as mirror stars at Atami meeting in 1996 (Blinnikov, 1998). This interpretation is proposed also by Silagadze (1997). Recently, the idea is developed by Foot (1999) and Mohapatra & Teplitz (1999). A very important evidence that MACHOs cannot be stars made of ordinary baryons is presented by Freese *et al.* (1999).

The ghost world that interacts with ordinary matter exclusively via gravity follows quite naturally from some models in superstring theory (see, e.g., recent results by Chang *et al.*, 1996, Faraggi, 1997), but those models are too poor to be useful in the GRB problem. Especially interesting for explaining GRBs are the models that predict the existence of a light sterile neutrino that can oscillate into ordinary neutrino. The development of the idea can be traced from the following references.

The ordinary neutrino oscillations was first discussed by Pontecorvo (1958), who pointed out the analogy with $K_0 \leftrightarrow \bar{K}_0$ oscillations. For the mirror matter searches, Nikolaev and Okun (1968) also considered kaons. The mirror neutrino oscillations have drawn the interest of researchers later. Interesting oscillation phenomena for ‘paraphotons’ were considered by Okun (1982).

Foot *et al.* (1991) rediscovered the idea of mirror particles. They assumed that the neutrinos are massless and showed that there are only two possible ways in addition to gravity, that the mirror particles can interact with the ordinary ones, i.e. through photon-mirror photon mixing

(this had already been discussed earlier, in a slightly different context, by Glashow, 1986), and through Higgs-mirror Higgs mixing. In another paper, Foot *et al.* (1992) have shown that if neutrinos have mass, then the mirror idea can be tested by experiments searching for neutrino oscillations and can explain the solar neutrino problem (though, see Gonzalez-Garcia *et al.*, 1999).

The same idea can also explain the atmospheric neutrino deficit (recently confirmed by SuperKamiokande data), which suggests that the muon neutrino is maximally mixed with another species. Parity symmetry suggests that each of the three known neutrinos is maximally mixed with its mirror partner (if neutrinos have mass). This was pointed out by Foot (1994). Finally, the idea is also compatible with the LSND experiment which suggests that the muon and electron neutrinos oscillate with small angles with each other, see Foot & Volkas (1995).

Berezhiani & Mohapatra (1995) developed a different model with parity symmetry spontaneously broken. In this model the mirror particles have masses differing from the masses of their ordinary counterparts. The model gives a natural explanation why the primordial nucleosynthesis constraint (Shvartsman, 1969) does not preclude the existence of relativistic mirror particles. Several solutions to this are possible also in the Exact Parity Model (Hodges, 1993; Foot, Volkas, 1995, 1999).

7 Dark matter candidates and GRBs

The idea to connect the Dark Matter (DM) and GRBs is not new. E.g. Loeb (1993) considered axions, produced by collapsing stars, and their decays to gammas. This model does not directly involve DM stars, but axions remain a plausible candidate for DM. Recently other models involving axions and axion stars, and other exotic particles are suggested (Bertolami, 1999; Demir and Mosquera Cuesta, 1999; Iwazaki, 1999). They predict a relatively weak GRB, so to explain the observed afterglows they refer to our ‘mini supernova model’ (Blinnikov, Postnov, 1998) for a GRB bursting in a binary system. This can help with the visual light but cannot increase the power of the gamma radiation itself.

I suggest another scenario. I propose that Gamma-ray Bursts (GRB) are produced by collapses or mergers of mirror stars. The mirror neutrinos (which are sterile for our matter) are born at these events in a way similar to what one can expect for ordinary stars. See e.g. the Fig. 8, taken from Janka *et al.* (1998), but imagine, that all emitted neutrinos are the mirror ones. The latter can oscillate into ordinary neutrinos. The annihilations or decays of those create an electron-positron plasma and subsequent relativistic fireball with a very low baryon loading needed for GRBs.

In speculating about such a scenario it is instructive to assume that the properties of mirror particles are the same as in our world. I wish to stress here that this is not absolutely necessary. E.g. the model by Berezhiani & Mohapatra (1995) with masses of nucleons in the mirror world higher by a factor ~ 1.5 , predicts that there is no nuclear burning in mirror stars, because the mass difference between mirror neutron and proton is predicted to be ~ 100 MeV, while mirror electron has mass ~ 30 MeV. Yet this does not preclude the formation of white dwarf or neutron star (Berezhiani, 1996) binaries and their merging due to gravitational wave emission. A result of this merging can be a catastrophic collapse to a rotating black hole accompanied by the formation of accretion disk and huge neutrino flux. In what follows I assume for simplicity that not only the pattern of particles in the mirror world, but all their properties are the same as in the visible one (Kobzarev *et al.*, 1966; Foot & Volkas 1995).

If the properties of mirror matter are very similar to the properties of particles of the visible world, then the events like neutron star mergers, failed supernovae (with a collapse to a rotating black hole, Woosley, 1993; Macfadyen, Woosley, 1999) etc. must occur in the mirror world. These events can easily produce sterile (for us) neutrino bursts with energies up to $10^{53\div 54}$ ergs, and the duration and beaming of mirror neutrinos are organized naturally like for ordinary neutrinos in the standard references given above. The neutrino oscillations then take place which transform them at least partly to ordinary neutrinos, but without the presence of big amounts of visible baryons. Some number of ordinary baryons is needed, like $10^{-5}M_{\odot}$ (Piran, 1999b) for producing standard afterglows etc. This number is easily accreted by mirror stars during their life from the uniform ordinary interstellar matter (cf. Blinnikov and Khlopov, 1983).

Taking into account magnetic moment of standard neutrinos can help in producing a larger variety of GRB variability due to neutrino interaction with the turbulent magnetic field inevitably generated in the fireball. This is good for temporal features similar to the observed fractal or scale-invariant properties found in gamma-ray light curves of GRB (Shakura *et al.*, 1994; Stern and Svensson, 1996). Another extension of the model is possible if heavier neutrinos can decay into lighter ones producing photons directly (see e.g. Jaffe & Turner, 1997). Invoking a magnetic field helps to explain a rich variety of properties of GRBs even for zero neutrino magnetic moment, as suggested by Kluźniak & Ruderman (1998) for ordinary matter.

Neglecting matter effects on the parameters of neutrino oscillations, one can estimate that the oscillation length required in this scenario must be less than the size of the system (10 – 100 km) multiplied by the square root of N_{sc} – the number of scatterings of mirror neutrinos. E.g. in the body of a mirror neutron star, with optical thickness to neutrino extinction equal to τ , we have $(N_{\text{sc}})^{1/2} \sim (\tau)^{1/2} \sim 10^3$. This estimate obtains if one takes into account that after each interaction of neutrino the coherence is lost and the oscillation process start anew (e.g., Raffelt, 1996). The number N_{sc} can be much less in the accretion disk.

This is correct only if the matter does not influence the parameters of neutrino oscillations, e.g. if δm^2 is big. In reality the properties of oscillations do change drastically if the parameter

$$X = 2\sqrt{2}G_{\text{F}}nE/\delta m^2 - \cos 2\theta_{\text{v}} \quad (18)$$

is large (Wolfenstein, 1978, Mikheyev & Smirnov, 1985), see reviews in Raffelt (1996), Smirnov (1998), Haxton (1999). Here θ_{v} is the vacuum mixing angle and n is an effective number density of the relevant particles. In the case $|X| \gg 1$ one has

$$\sin 2\theta \simeq \sin 2\theta_{\text{v}}/|X|$$

for the effective mixing angle θ , so the probability of the neutrino transformation is strongly suppressed. The expression (18) is OK, say, for $\nu_e - \nu_{\mu}$ oscillations in hydrogen plasma (no neutrons) when the neutrino density is not high (e.g. in solar interiors), when n is equal to electron number density, $n = n_e$. In presence of neutrons with the concentration n_n , the amplitude of the coherent weak interaction of ν_e changes and $n = n_e - n_n/2$ (Voloshin *et al.*, 1986; Voloshin, 1988). When n_{ν_e} is not negligible, it is more complicated since the neutrino-neutrino interactions are also important and one has $n = n_e - n_n/2 + 2n_{\nu_e}$ (Okun, 1988). The adiabatic change of sign of $X(r)$ inside a collapsing star allows a resonance (i.e. complete) transformation of neutrino flavors as in Mikheyev & Smirnov (1985) mechanism. Now the location r of the resonance is determined primarily by the root of $n(r) = 0$ (Voloshin, 1988; Blinnikov, Okun, 1988; Akhmedov *et al.*, 1997).

For transformation of sterile neutrinos during collapse the situation is analogous and one has to add to n the appropriate concentrations of neutrinos of all flavors (e.g. McLaughlin *et al.*, 1999).

Volkas and Wong (1999) considered recently the role of neutrino oscillations for the mirror matter model of GRBs (though without taking into account the neutrino contribution to n). They find that for a *spherical* collapse of a mirror star the oscillations occur at a large radius r above the neutrinosphere. But for $r \gg R_\nu$ the estimate (14) shows that the power of annihilations falls as $(R_\nu/r)^5$. Volkas and Wong (1999) conclude, that a GRB event will be too weak, but this argument does not kill the mirror GRB model. In reality, a spherical collapse in the mirror world should not give a powerful GRB – otherwise they would be observed too frequently (like each 10 – 100 years per a galaxy, but their statistics is like one per million, or 10 millions years per a galaxy). Only rare events, like merging neutron stars, or massive collapses with rotation are needed to produce GRBs. But in a highly non-spherical geometry the transition to a low density medium takes place on the same length-scale as the size of the system, R_d in (13). Moreover, the jets formed in those systems reduce the density of mirror matter, so the neutrinos can oscillate at higher average energy $\langle E \rangle$, making a more powerful GRB event, cf. (13).

8 Conclusion: arguments in favor of mirror matter models

Recent discoveries of GRB afterglows put the bursts at cosmological distances. This leads to the energy and to the compactness problems in GRB models. The models involving collapses and mergers of ordinary stars are only marginally successful in explaining these events. The restrictions on the properties of Dark Matter show that it cannot consist of ordinary baryons. On the other hand the discovery of MACHO microlensing events and explanation of rotation curves of galaxies suggest the existence of invisible matter and stars with properties similar to the properties of ordinary baryonic matter. This is a hint that a large fraction of the Dark Matter can be in a form of mirror particles. There are models that explain the neutrino experiments by oscillations of ordinary neutrinos to their sterile mirror counterparts. The mirror neutrinos that must be abundantly produced at mergers of mirror star can produce a powerful gamma-ray burst after oscillating to ordinary neutrinos in the space with a very low contamination of ordinary baryons.

Summarizing, here are the arguments in favor of the proposed scenario.

1. The mirror matter is aesthetically appealing, because it restores the parity symmetry of the world (at least partly).
2. It allows to explain the observed neutrino deficits.
3. It explains the galactic missing mass, and in some models the Dark matter in general.
4. It explains MACHO microlensing events.
5. For GRBs it provides the model with the low baryon loading, if the mirror neutrinos oscillate to the ordinary ones.
6. Matter effects on the neutrino oscillations suppress the production of gamma-rays in the quasi-spherical collapses. This is in agreement with statistics of powerful GRBs which must be caused by rare events like merging of mirror neutron stars.

7. The available baryon loading on the scale of the mass of a small planet is exactly what is needed for fireball models.
8. All host galaxies for optical transients of GRBs are strange ones. This may be an indication for the gravitational interaction of the ordinary galaxy with the mirror one in which it can be immersed.

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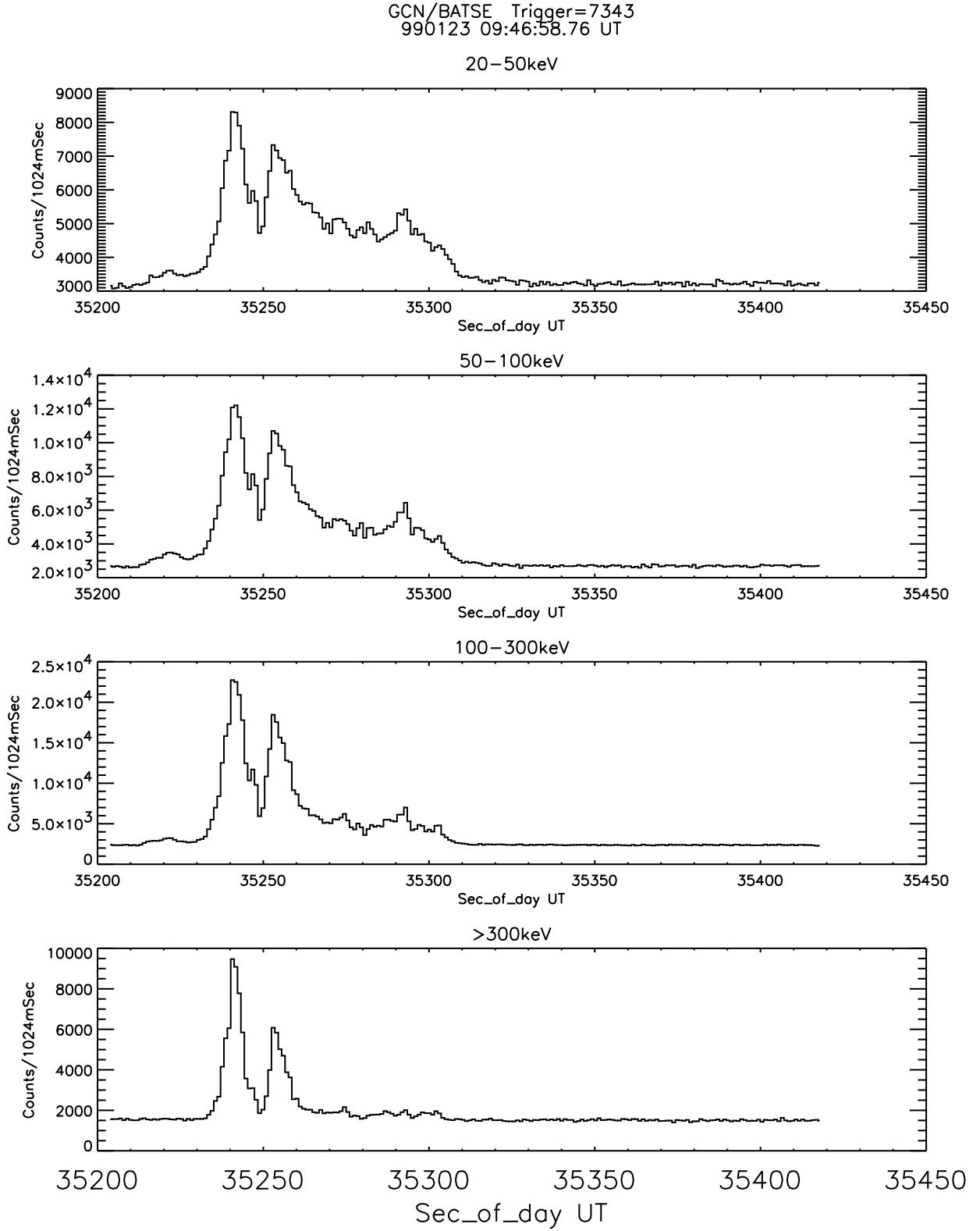


Figure 1: BATSE fluxes in four channels for GRB 990123 (source: <http://gcn.gsfc.nasa.gov/gcn/>)

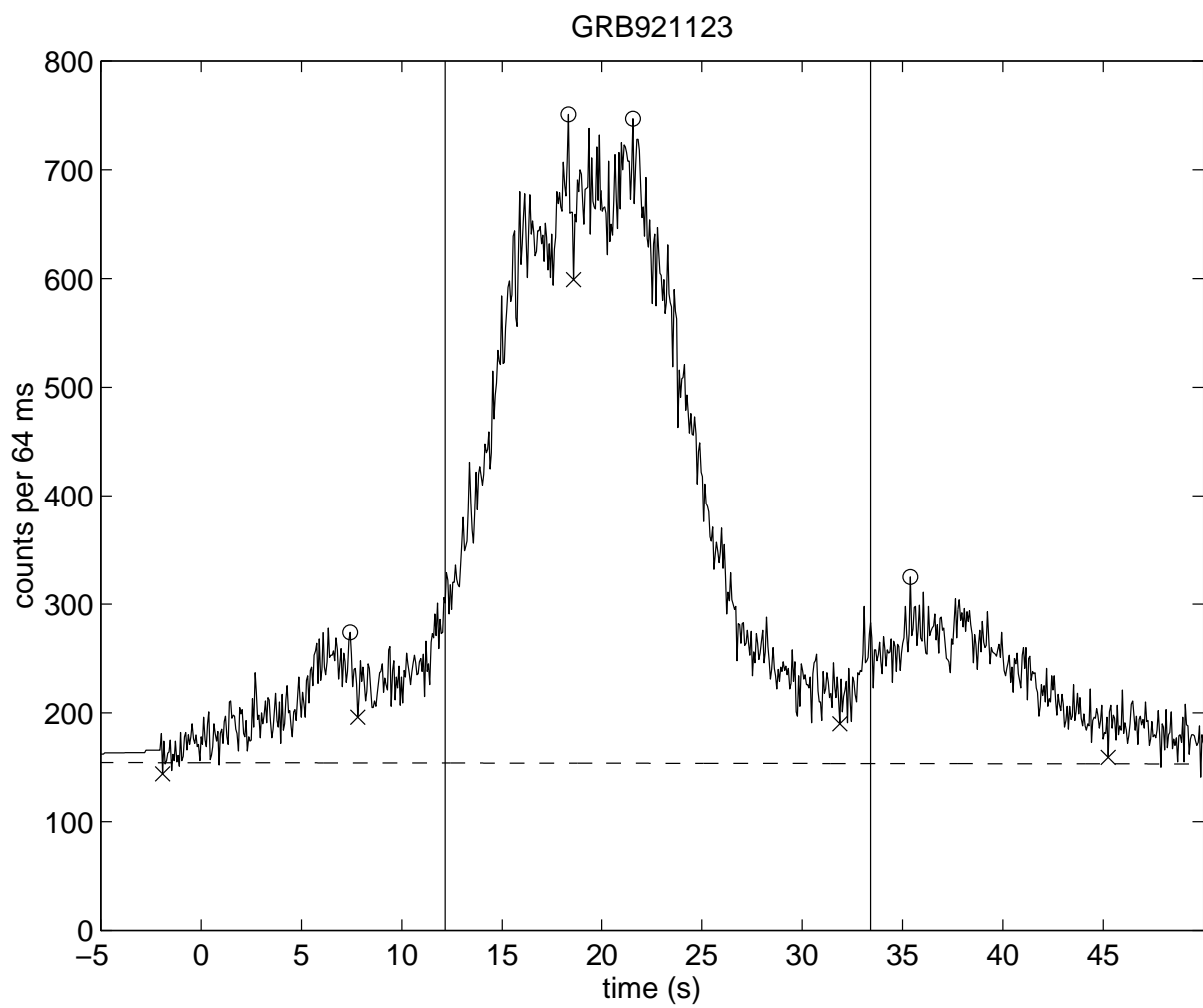


Figure 2: A smooth, single pulse, light curve (counts vs. time) of GRB 921123 (source: Cohen *et al.*, 1997)

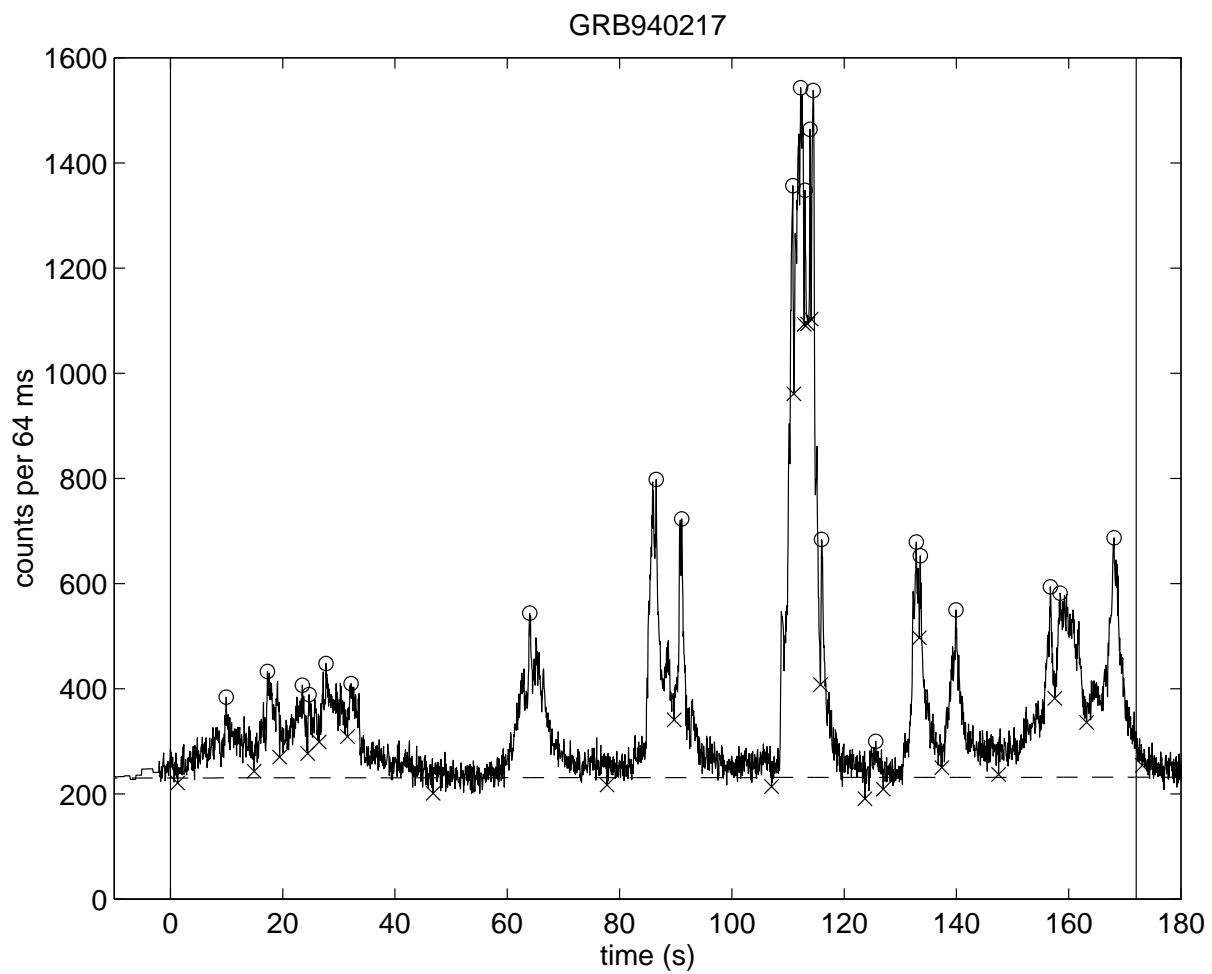


Figure 3: Multiple pulses in the light (counts vs. time) of GRB 940217 (source: Cohen *et al.*, 1997)

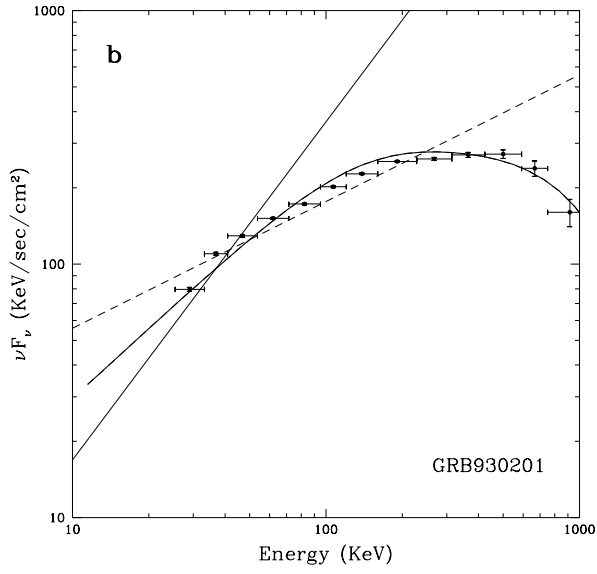
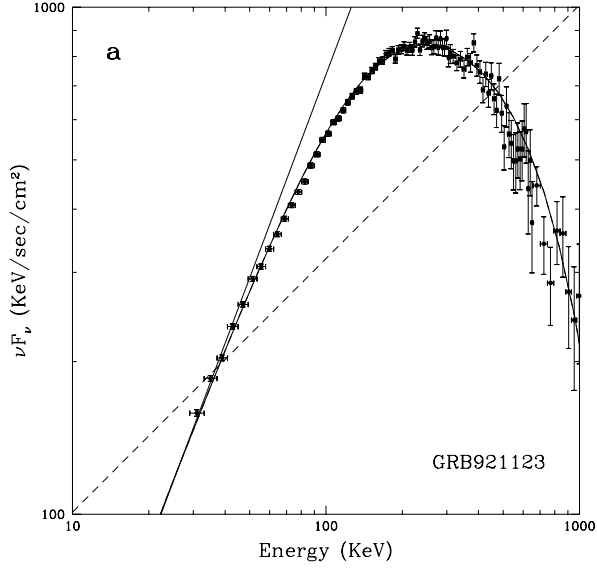


Figure 4: Spectra a) GRB 921123; b) GRB 930201 (source: Cohen *et al.*, 1997; fits Blinnikov *et al.*, 1999)

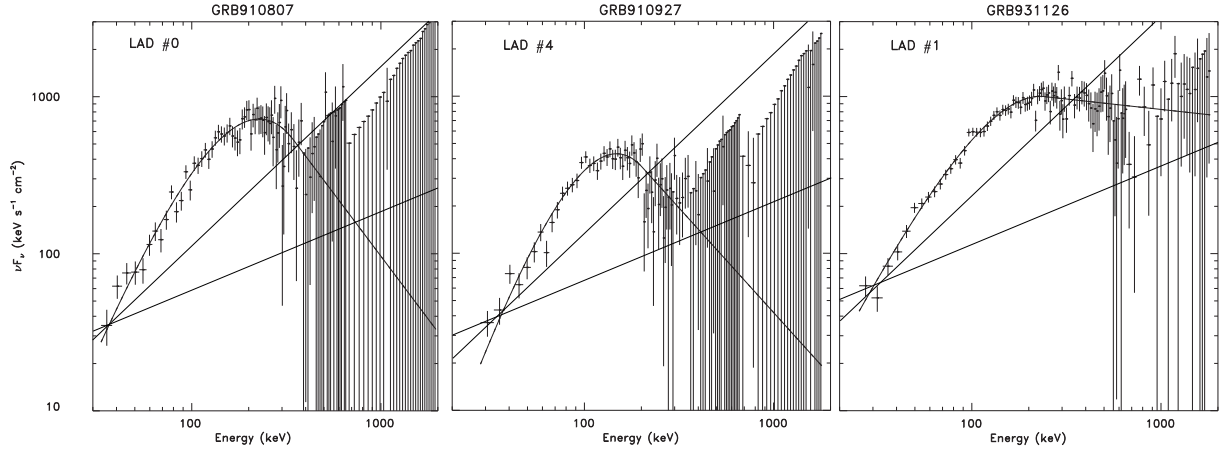


Figure 5: GRB spectra, that are steeper at low-energy than allowed by the synchrotron shock model (source: Crider *et al.*, 1997)

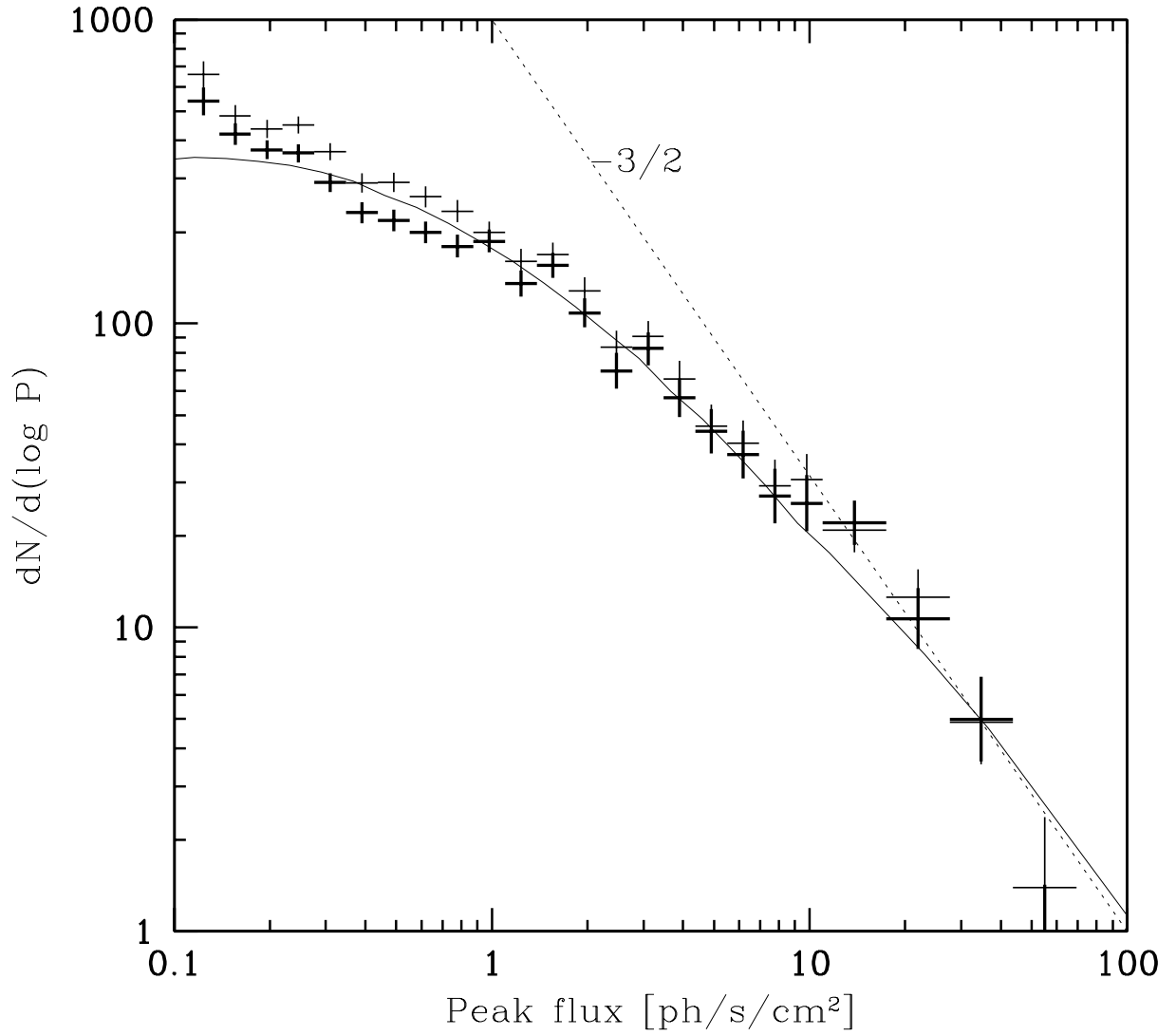


Figure 6: The differential $\log N_s - \log S$ distribution from Stern *et al.* (1999). Here P denotes the peak flux S . The full distribution is shown by thin crosses. Thick crosses are for the case when short bursts are removed.

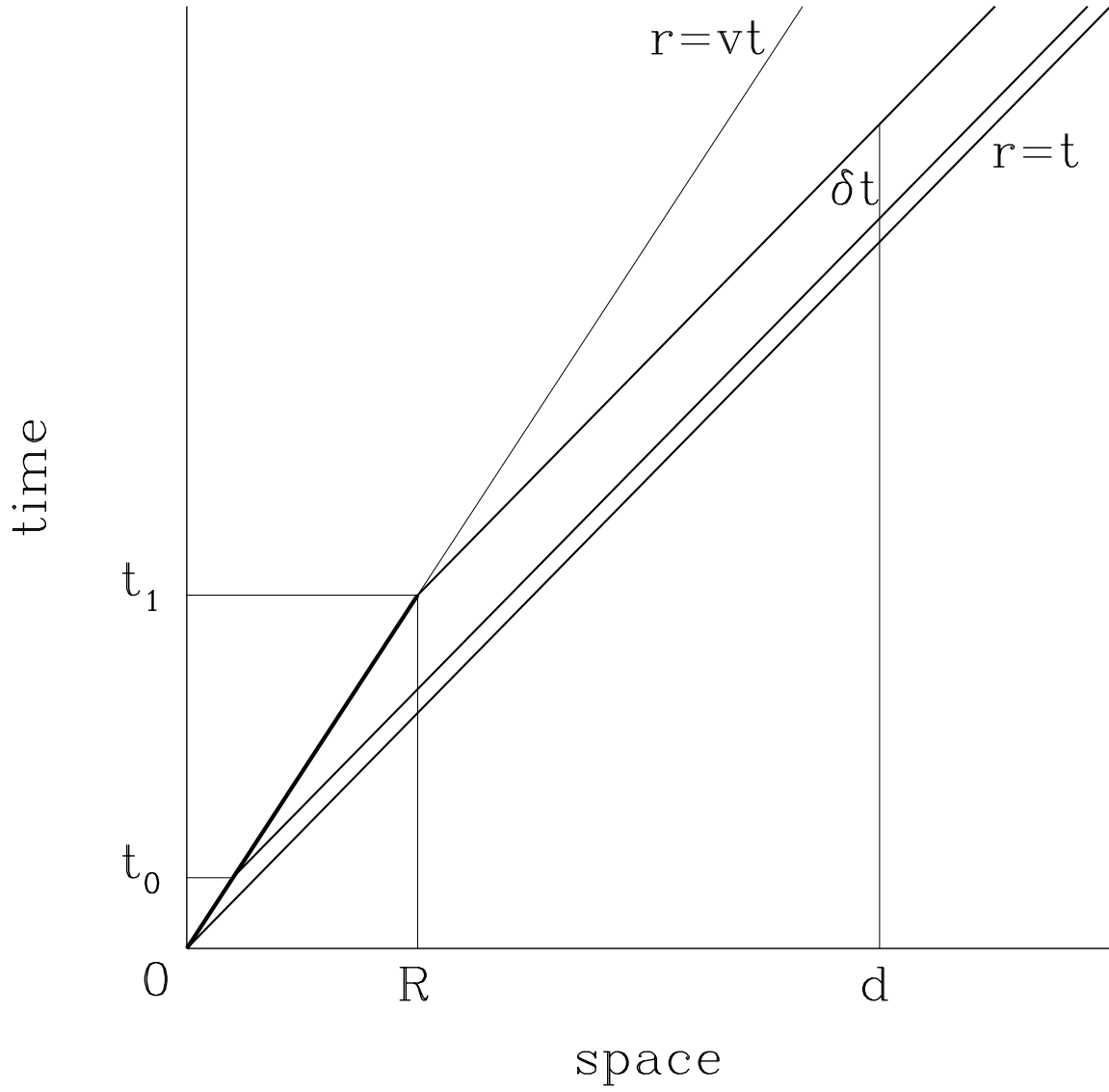


Figure 7: The space-time diagram for the emission of a shell (thick solid line) expanding with the speed v . Emission begins at $t = t_0$ and ends at $t = t_1$, when the shell has the radius R . The observer at rest at distance d detects the duration of the radiation pulse $\delta t = (t_1 - t_0)/2\Gamma^2 \ll t_1 - t_0$.

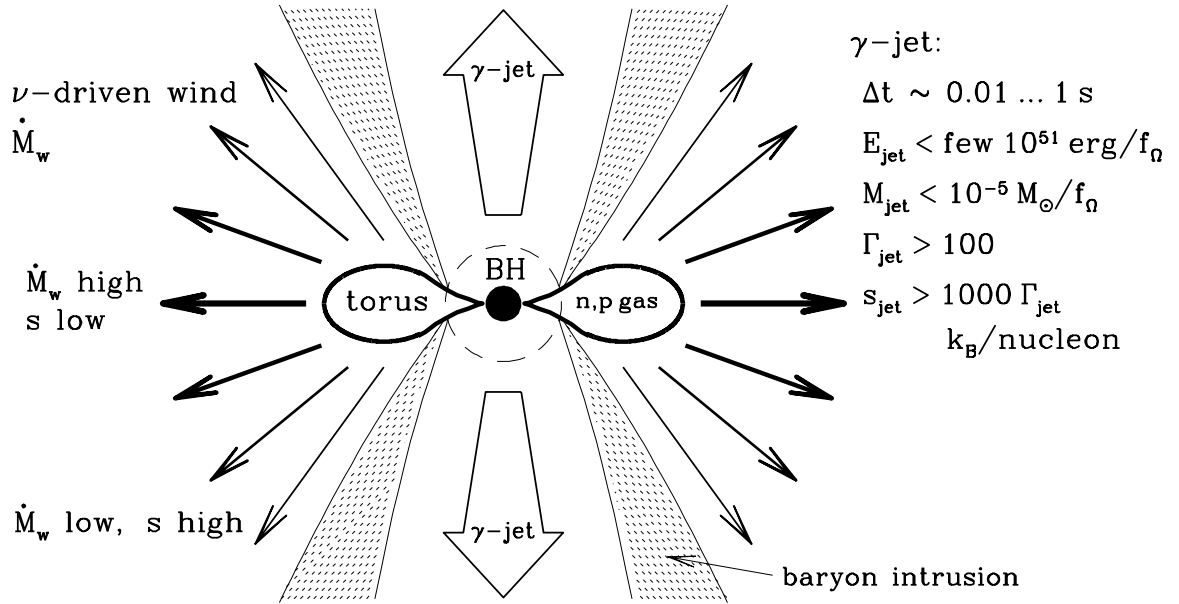


Figure 8: A sketch of a jet near the black hole (BH) formed after the merging of two neutron stars (source: Janka *et al.*, 1998)